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ARTICLE

Environmental cognitions mediate the causal explanation of land change

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ABSTRACT

Causal explanations of land change are fundamental in land system science, yet existing findings are difficult to synthesize due to the imprecise terminology and the various analytical frameworks they have applied. This paper compares three existing conceptual frameworks, in terms of underlying driving forces and proximate causes, actors, and environmental cognitions, by aligning the relevant elements into a causal chain. We find that the elicitation of environmental cognitions helps in providing a detailed description of this causal chain. By synthesizing case study evidence on agricultural land change into the generalized causal chain, we find that the effects of underlying driving forces on land change have been substantially mediated by environmental cognitions. Operationalizing environmental cognitions requires more efforts than regular actor-based studies, but a proper understanding of its mediating role should be accounted for in local scale studies and is essential for human-centred policy design.

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Attitude; causal chain; decision-making; driver; land use change; perception

1. Introduction

Land systems reflect the state and results of activities of humans interacting with the natural environment: these result from the combination of socioeconomic and biophysical processes, and bring about various benefits gained from land as well as unintended social and ecological outcomes (Verburg et al., 2015). Land systems are constantly changing, including changes in land cover (the physical properties of the vegetation and land surface) and changes in land use and management (the purposes and activities for and through which humans influence the land) (Reenberg, 2009; Rounsevell et al., 2012; Verburg et al., 2015). As land use and land cover changes – together referred to as land change – have important consequences for ecosystems and the environment (Verburg et al., 2015), it is essential to understand the causes of these changes to improve land management.

Scientists undertake research to discover the causes of an outcome, which is referred to as causal analysis/explanation (Efroymson et al., 2016; Meyfroidt, 2016). Little (1996) pointed out that, in general, there are four types of causal relations between A and B, namely (i) causal regularity: A is always followed by B; (ii) necessary and sufficient condition: A is a necessary and/or sufficient condition for B; (iii) causal mechanism: there exists a chain of causal mechanisms leading from A to B; and (iv) probabilistic causation: the occurrence of A raises the probability of the occurrence of B. However, the terminology and

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approaches used for causal analysis in land system science, represented by terms like underlying driving forces, proximate causes, driving forces, determinants, human decision-making, actors, cognitions, etc., remains imprecise (Müller, 2016). These concepts are difficult to reconcile and make it hard to compare the reported evidence in case studies.

Meyfroidt (2016) suggests to use 'cause' to explain land change given its simplicity and explicitness and elaborates that much of the work in land system science falls under 'historical sciences', rather than being tested in the laboratory. This suggests that the application of causal regularities is not appropriate in this field. Instead, a cause of land change can often not be distinguished and land changes are often part of a combination of causes with interactions impacting on the direction and/or strength of the relation between causes and outcomes. Meyfroidt (2016) further highlights the general rule that the more discrete steps are introduced in a causal chain, the more convincing a causal explanation is. This is reconfirmed in papers by Elster (2015) and Efroymson et al. (2016), but not often put into practice.

In the literature different approaches are used in which land change outcomes are connected to the underlying driving forces. In many studies, only a direct connection is made (van Vliet et al., 2016). In some cases, these outcomes are explained by including land manager' characteristics (e.g. age, gender, education, income, etc.) and in some cases their environmental cognitions (e.g. perception, awareness, attitude, willingness, etc.). Underlying these different approaches applied in case studies are a few structured analytical frameworks, which describe the roles of underlying driving forces and proximate causes, actors, and environmental cognitions, respectively, see the reviews by Geist and Lambin (2002), Kaimowitz and Angelsen (1998), Hersperger, Gennaio, Verburg, and Bürgi (2010) and Meyfroidt (2013a). In this paper, we compare these commonly used frameworks, and align the relevant elements into a causal chain, based on which we discuss how the discretization of the causal chain can be achieved. We give specific attention to the role of environmental cognitions as these are hypothesized to play a crucial role in understanding the causal processes in land change. We review a few relevant case studies to illustrate how environmental cognitions mediate the causal explanation of land change and discuss how the findings could be further operationalized in case-based research.

2. Description and comparison of causal analysis frameworks

2.1. Frameworks description

We first describe the commonly used causal analysis frameworks which include the notions of underlying driving forces and proximate causes, actors, and environmental cognitions based on their original publications.

Geist and Lambin (2002) proposed a framework of underlying driving forces and proximate causes to analyse land cover change, where proximate causes are the human activities or immediate actions of land use that take place at a location, while underlying driving forces denote the fundamental social or biophysical processes that drive these proximate causes. The framework was largely based on earlier works from Meyer and Turner II (1992) and Turner II et al. (1995), and has been originally used to explain the causes of changed land cover patterns such as deforestation (Geist & Lambin, 2002) and desertification (Geist & Lambin, 2004).

In an early work from Kaimowitz and Angelsen (1998), actor's characteristics have been addressed explicitly as part of explaining deforestation decisions. Later on, Hersperger et al. (2010) summarized the different conceptualizations between three crucial elements: driving forces, actors, and land change. Land change (C) refers to change in land cover or land use, which is measured by comparing land cover/land use at two or more points in time. Underlying driving forces (DF) are the forces that – together with actors – shape land change. Actors (A) make decisions, act accordingly, and trigger land change with their actions. Four basic models are presented describing the relation between driving forces and land change: (i) DF-C model: driving forces are directly related to land change; (ii) DF-A-C model: driving forces affect actors and actors subsequently cause change; (iii) DFA-C model: driving forces and actors are in close interaction, and as a result of this interaction, change occurs; and (iv) the A-C model: actors play the central role in land change and are seen as a driving force in itself.

Meyfroidt (2013a) outlines three components that are linked in a feedback loop: environmental changes, environmental cognitions, and land use practices. The framework has been further specified as: (i) land-use choices result from multiple decision-making processes, and rely on various motives influenced by social norms, emotions, beliefs, and values toward the environment; (ii) social-ecological feedbacks are mediated by environmental cognition, that is, the perception, interpretation, evaluation of environmental change, and decision-making; and (iii) human agents actively re-evaluate their beliefs, values, and functioning to adapt to unexpected environmental changes. This feedback loop can be simplified as: perceiving an environmental signal, and crafting a causal explanation to it.

2.2. Framework comparison

The different analytical frameworks described above can be compared using the terminology proposed in Meyfroidt (2016) and the basic distinctions made by Hersperger et al. (2010). This comparison is organized based on a generalized causal chain, linking the causes (from the conditions) to the outcomes of land change (Figure 1).

Figure 1 is firstly elaborated vertically, with all elements compiled into a generalized causal chain. Outcomes of land change – the *explanandums* of causal analysis (Meyfroidt, 2016) – are standing at the top of the causal chain. In land system science, the outcomes of change have been organized from a focus on the more dramatic land cover changes to greater attention for subtle

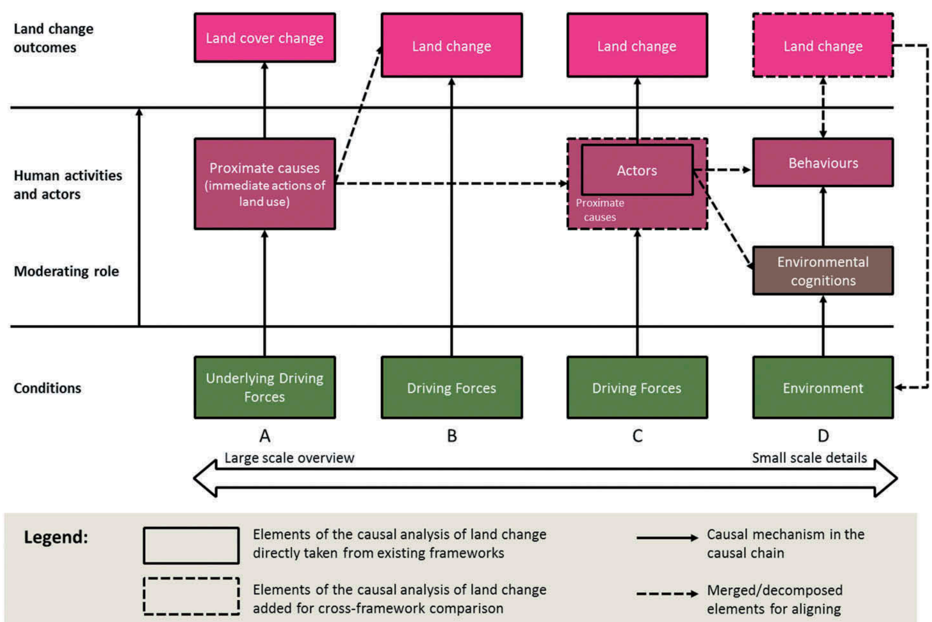

Figure 1. Diagram for cross-framework comparison. Vertically, the boxes with specific colour are the aggregated elements that contain multiple outcomes or causes aligning in a generalized causal chain. Horizontally: (**a**) is the framework of underlying driving forces and proximate causes; (**b**) is the DF-C model from Hersperger et al. (2010); (**c**) is the combination of DF-A-C, DFA-C and A-C model from Hersperger et al. (2010); (**d**) is a modified representation of the environmental cognition loop from Meyfroidt (2013a). The labels of each box are adopted according to the original expressions which are comparable to each other.

changes of human interactions with the natural surroundings, including land management and the provisioning of a wide range of ecosystem services (Verburg et al., 2015). Thus, from this perspective, the land change outcomes should be clearly identified in the first place for a causal analysis, with a clear statement of the problem, and followed by the generation of hypotheses to explain changes and causal pathways (Efroymson et al., 2016). In Figure 1, bright purple boxes present land change outcomes. Because land use changes were known as proximate drivers that underpin land cover change (Geist & Lambin, 2002), they are separated first (i.e. in Framework A) and then combined subsequently (i.e. in Framework B, C and D).

Except the *explanandum*, other elements in the causal chain are all known as *explanans*, i.e. the causes (Meyfroidt, 2016). Although the terminology is not unified among the selected frameworks, causes from the socioeconomic–biophysical environment form a fundamental set, placed at the lower end of the causal chain: the conditions. Six groups of causes at the underlying level are commonly identified: political, economic, cultural, technological, population, and natural driving forces (Geist & Lambin, 2004; Hersperger et al., 2010; van Vliet, de Groot, Rietveld, & Verburg, 2015). The green boxes in Figure 1 present these conditions, which are comparable to each other. While the labels of each box are adopted according to the original expressions.

Human activities on land use have been specified as the proximate causes that immediately bring about land change, and are underpinned by the underlying conditions. Consequently, they link land change outcomes and conditions in the causal chain (Figure 1). The role of human activities is scale-dependent. For example, agricultural expansion is one of the human activities that causes deforestation in the tropics. However, not every individual farmer in the tropics has expanded farming. Therefore, the role of individual actors needs to be further specified to indicate that land change outcomes are the aggregated consequence of human behaviour. Studies of these aspects aim to identify what (aggregated) human activities caused land change, or what actor characteristics – together with their conditions – influenced actors' behaviour and subsequently caused land change. The dark-purple-coloured boxes are used to indicate the role of human activities and actors in Figure 1.

In addition to actors' characteristics, which largely and directly determine the decision-making processes, Meyfroidt (2013a) and Schlüter et al. (2017) suggests that the black box of actors' decision-making processes can be unfolded by introducing environmental cognitions, which connect and mediate the relation between underlying conditions, actor's characteristics and decisions. Mediating variables are defined as those variables that mediate between the dependent and the independent variables (Baron & Kenny, 1986) (Figure 2 right part). According to Meyfroidt (2013a), environmental cognitions are the cognitive features that relate to the surrounding environment, e.g. perception, interpretation, understanding, evaluations of environmental change, and to activities that take place in relation with nature. This definition can be understood as a specification of cognition as used more broadly in other disciplines, such as biology, psychology, and anthropology (Reader, 2014), focusing on the cognitive processes in the human-environment context only. According to Baron and Kenny (1986), there are moderators in addition to mediators, which affect the direction and/or strength of the relation between dependent and independent variables, rather than explaining the relationship between these two (Figure 2, left part). Environmental cognitions play a mediating role because they are neither part of the conditions nor the land change outcomes. Other cognitive outcomes, e.g. belief, value and norms play a moderating role because how environment affects decision-making through the mediation of them is lesser concerned (Figure 2, left part). Therefore, the moderating role of cognitions can be considered as a nested effect of actor characteristics. The brown box in Figure 1 represents mediating role of environmental cognitions in land change.

Figure 1 is then elaborated horizontally to allow a better comparison of frameworks. The presented frameworks serve different purposes. Framework A is specifically developed for explaining the land cover change in a straightforward and simple manner (Geist & Lambin, 2002). For example, agricultural expansion is indicated as one of the proximate causes for forest

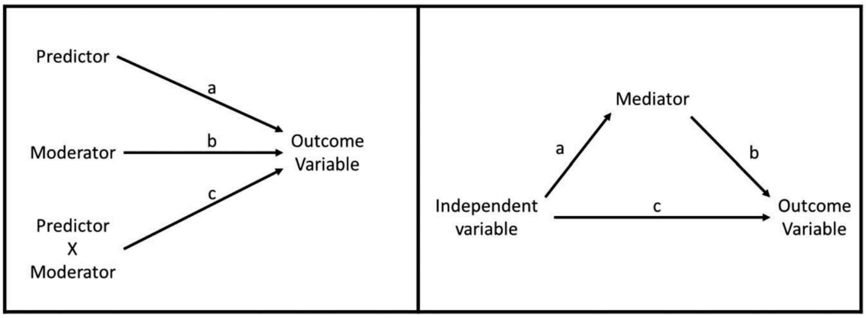

Figure 2. Different roles of moderators and mediators in causal explanations, The figure is adapted from Baron and Kenny (1986).

cover change (simplified as: land use change causes land cover change). Proximate causes, in turn, are underpinned by multiple different underlying driving forces. However, agricultural expansion per se is a land change outcome, while its proximate causes cannot be discussed within the same framework. Therefore, from the outcomes' perspective, Framework A is precise but less inclusive than the others, and thus requires adjustments in order to explain more subtle changes at the land use level, such as changes in land use management (van Vliet et al., 2015). We use dashed arrows in Figure 1 to indicate that the proximate causes and the resulting land cover change together are the equivalent of land change.

The combination of proximate causes and the resulting land cover change is shown in Framework B, which is the DF-C model in Hersperger et al. (2010). The idea of relating land change outcomes directly with the conditions has been applied to studies of land cover change, such as urban expansion (Liu, Zhan, & Deng, 2005), forest transitions (Langner, Miettinen, & Siegert, 2007), and land cover configuration (Long, Tang, Li, & Heilig, 2007), as well as studies of land use change, including grassland degradation (Li, Verburg, Lv, Wu, & Li, 2012), land use intensity (Levers, Butsic, Verburg, Müller, & Kuemmerle, 2016), and land-management regimes (Jepsen et al., 2015). Merging proximate causes and the resulting land cover change broadens the applicability of Framework A, but neglecting human activities might yield imprecise causal explanations. It is less convincing because the same set of causes are applied to explain multiple land change outcomes, and because not all actors will act similarly given the same conditions.

Framework C deepens Framework B by considering the role of actors. First, actors' land use behaviours are multi-faceted, ranging from converting the land cover to increasing the intensity of land use. Therefore, considering the decision-making processes provides more straightforward linkages to the multiple outcomes of land change. Second, land change can be regarded as the result of actor's behaviour at an aggregated level. Thus, the outcome of causal explanation can be switched from land change to behaviour, which enables the inclusion of the decision-making processes of individual actors. Framework C combines the DF-A-C, DFA-C and A-C model from Hersperger et al. (2010). According to the original description, DF-A-C attempts to answer 'which driving forces affect actors and how do they subsequently cause change?', DFA-C centres on the question 'how is land change a result of the interaction of driving forces and actors?', while A-C concerns 'how does the actor's reasoning, values, biographies, and household characteristics affect land use decisions?'. Such differences may slightly result in different causal explanations. However, regardless of the emphasis – sequence in the DF-A-C, interactions that have been regarded as black boxes in the DFA-C, and actors' attributes in the A-C – there are no extra features added among the three models to further discretize the causal chain. Therefore, we group these models to emphasize the role of individual actors and present it as Framework C. In comparison to Framework A, proximate causes are the actors' behaviours at an aggregated level (Figure 1), and it is known as 'actors in proximate causes' according to Hersperger et al. (2010). The inclusion of actors extends the causal chain. For example, it modifies the theory of rational actors – also referred to as the theory of homo economicus – to the theory of bounded rationality for explaining decision-making (Schlüter et al., 2017), which could result, potentially, in more precise causal explanations. As such it enriches the analysis of land change case studies with a bottom-up perspective, provides opportunities for agent-based land change modelling (Castella & Verburg, 2007), and improves understandings that synthesize land change processes from multiple cases (van Vliet et al., 2016).

Framework D is a modification of the environmental cognition loop from Meyfroidt (2013a). It further deepens Framework C: decision-making under the theory of bounded rationality is not only determined by actors' characteristics but also mediated by actors' environmental cognitions. The relevance of environmental cognitions is illustrated by several studies from relevant fields. For example, the perception of climate change varies significantly among people even if they have experienced the same climate change trend (Myers, Maibach, Roser-Renouf, Akerlof, & Leiserowitz, 2013). A perception gap exists and this could explain why people have deviating perceptions of the same phenomenon (Ropeik, 2012), which in turn affects their behaviour. This example indicates that perceptions and decisions are interrelated but vary at the individual level. As a result, the exclusion of environmental cognitions would yield uncertainties in predicting the consequences of environmental changes, due to variations in human perceptions of the environment (Milliken, 1987). Framework D elicits the role of environmental cognitions, through which the influence of conditions is mediated by actors. As a result, the causal chain is further discretized, which could lead to more convincing causal explanations (Elster, 2015). We use two dashed arrows to decompose actors' decision-making processes in Figure 1. Moreover, land changes – the consequences of human land use behaviour – are part of the environment, which could, in turn, affect environmental cognitions within a feedback loop (Meyfroidt, 2013a). Therefore, land change is represented in a dashed box and is linked to the environment through a dashed line in Figure 1.

The socioeconomic–biophysical conditions are not discussed in detail here, because they have been included in each of the compared frameworks under slightly different names. The complexity of the compared frameworks increases gradually from A to D. However, it does not mean that more complex frameworks are always preferable. For example, acquiring data on the mediating role of environmental cognitions is not straightforward, and requires large resources. This suggests that understanding the causes of land change especially depends on the research scope and questions (Hersperger et al., 2010): the more simplified frameworks are suitable for getting the large scale overview, and the more complicated frameworks are designed for exploring the details at a relative small scale (Figure 1).

3. Operationalization of environmental cognitions

Representation of the cognitive aspects is deficient in many land change studies (Filatova, Verburg, Parker, & Stannard, 2013). This may be because the parameterization and operationalization of environmental cognitions for explaining land change is still in its infancy. While environmental cognitions have received much attention in other fields of environmental science (Henry & Dietz, 2012), two challenges become apparent for its application in land change. Firstly, the concept of environmental cognitions in relation to land change is only broadly described, see Meyfroidt (2013a), which makes it difficult to determine which aspects are necessary to assess its mediating role. Secondly, as the mediating variables are the connectors between the outcome variables and the independent variables in the causal analysis (Baron & Kenny, 1986), it is even more difficult to parameterize environmental cognitions for a quantitative analysis.

The above challenges suggest the need for a simple and effective operationalization. Based on Meyfroidt (2013a) and a few relevant case studies, we suggest that at least two elements of environmental cognitions, i.e. perceptions and attitudes, should be measured to link the conditions

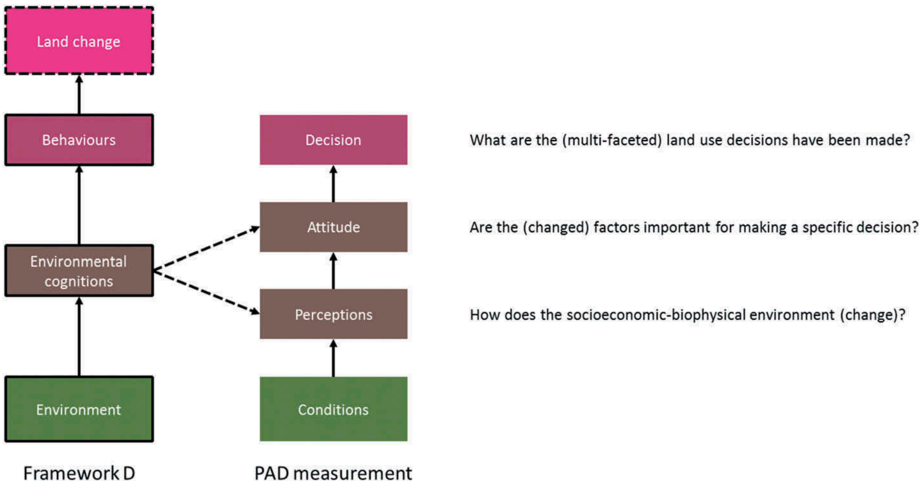

Figure 3. An operational measurement of environmental cognitions as the mediators in the causal chain of land change. Land changes are the direct consequences of human land use behaviours, thus it unnecessary to explicitly represent this in the PAD.

and decisions, and to form an additional set of causal mechanism (i.e. mediators) that decomposes the decision-making process (Figure 3). Beliefs and values are also proxies of cognitions (Meyfroidt, 2013a). We do not include them, because they often play a weaker mediating role between environment and decision-making, thus are regarded as moderators (see Figure 2). Except for conditions, the perceptions, attitudes, and decisions (referred to as PAD in the following) are usually measured by detailed interviews.

3.1. The measurement

Perceptions are the personal interpretations of reality, which form the basis of cognitive processes (Schacter, Gilbert, & Wegner, 2011). This personal experience can differ from reality, as illustrated for example by the variant perception of land change drivers amongst local farmers (Ariti, van Vliet, & Verburg, 2015). Such a difference in perception can lead to different cognitive processes and thus different behavioural actions. There are often inconsistencies (e.g. incorrect perceptions) between the observed environment and stated personal experiences (Kaiser, Wölfing, & Fuhrer, 1999). Therefore, analysing the relationship between people's perception and the physical reality not only improves our understanding of environmental change, but also helps to evaluate the reliability of survey results. Logically, a complete assessment requires recording both reality and human perception of the reality. Reality can often be measured properly, for example, by meteorological records or statistical data on socioeconomic, although these measurements sometimes suffer from flaws, uncertainties, biases and different definitions. The measurement for perceptions can be either qualitative or quantitative. For example, the qualitative measurement can be done by asking interviewees to report his/her perceptions on (changes in) environmental variables, e.g. increased/decreased/unchanged. A comparison of both will reveal the congruence or discrepancy between these different types of information.

Attitudes are the personal assessments on a subject and which influence his/her behaviour. They are constructed by individuals based on their personal experiences, perceptions and understanding of the world (Schacter et al., 2011). Attitudes can be represented explicitly as a differential factor in the typologies of land change actors, e.g. Jongeneel, Polman, and Slangen (2008) and Valbuena, Verburg, and Bregt (2008). Because land use decisions are multi-faceted, attitudes should be assessed toward a specific decision. An attitude is an interface between perception and decision, which means that impacts from conditions can differ among multi-faceted decisions and various decision-makers. However, certain factors that are stated to be important might not be revealed in the actual decisions (Eilam & Trop, 2012; Kaiser et al., 1999).

Decisions need to be observed before measuring the attitudes. This measurement can be simple: recording interviewees' experience of decision-making, in accordance with the explained land change outcomes. A (semi-) quantitative assessment of the corresponding attitudes is required to assess their influence on decisions, for example, by assigning points to a set of environmental variables to indicate their importance in a specific decision. A quantitative assessment is preferable to examine the causal relationship between stated attitudes and actual decisions.

3.2. Applications

We briefly review a few case studies to support the PAD measurement as an operationalization of environmental cognitions (Table 1). He, Lang, and Xu (2014) qualitatively measured local farmer's attitudes on forest transition in upland villages in Southwest China. Although environmental cognitions are explicitly addressed the analysis is rather descriptive. An earlier study by Greig (2009) evaluated farmers' stated causes in Tanzania – ranging from the attitudes on resource availability to the personal preferences – for making a crop choice. The similar ranking approach has been applied in Feike, Mamitimin, Li, and Doluschitz (2015), who assessed the causes of regional land and water use development in Northwest China through identification and ranking the causes by local experts. In addition, they briefly described the changes in conditions which made the elicitation of environmental cognitions more relevant. Meyfroidt (2013b) applied a qualitative approach to assess local villagers' environmental cognitions in northern Vietnam. He provided a comprehensive measurement that combines remote sensing data with field surveys, including interviews, group discussions, mental and participatory mapping, observations, and secondary sources. The feedbacks from environmental degradation and changes in the provision of ecosystem services to land practices via environmental cognitions were assessed, and the results showed that forest scarcity was perceived, interpreted and evaluated before possibly affecting land use practices.

Although these qualitative and descriptive analyses succeeded in depicting environmental cognitions, they have largely ignored making the connections between the different elements (Table 1). Yu et al. (2013) and Yu et al. (2014) applied quantitative approaches to investigate how farmers interpret environmental conditions, and how their attitudes towards socioeconomic and biophysical conditions affect two different land change decisions, i.e. land use right transfer (land transfer) and crop choice, in an agricultural region of Northeast China. Special in this approach is that tests were made to test the consistency between conditions, cognitions and decisions. The elements were successfully integrated into the generalized causal chain. Yu et al. (2013)'s method was further applied in Liu and Liu (2016), who examined the role of environmental cognitions in rural livelihood transitions in an east coastal region of China.

The key conclusions drawn from these illustrative cognition-based case studies are presented in Table 1. It shows that interviewees stated various factors that have influenced local land changes. It also clearly shows that more case studies have measured interviewees' attitudes for explaining the causes of land change, while the perceptions regarding the changes in the underlying environment are less frequently addressed, suggesting that full applications of PAD are really rare. Meyfroidt (2013b) assessed the attribution of land changes to natural/anthropogenic causes; nevertheless, he found that most interviewees have no early detection and recognition of environmental change due to very rapid changes or slow trends of degradation. The absence of measurements of the perception makes the attitude measurement less convincing. The two relevant case studies, i.e. Yu et al. (2013) and Yu et al. (2014) were designed to fully use PAD. Yu et al. (2014) indicated that human perception can differ from observed conditions, which suggests that observed land change

Table 1. Key conclusions drawn from the illustrative cognition-based case studies. A '*' indicates that the connections between perceptions and conditions are concerned, while a '**' indicates that the connections between stated attitudes and actual decisions are concerned in the case studies.

Case studies	Attitudes (stated by interviewees)	Perceptions (stated by interviewees)
Greig (2009): Kibamba Ward, Tanzania	Vegetable cultivation was influenced by the physical environment, the availability of machinery as well as certain economic factors.	NA
He et al. (2014): Yunnan, Southwest China	Forest transitions were influenced by off-farm opportunities, poor irrigation infrastructure on marginal cropland, external market, and fuel wood demand.	NA
Feike et al. (2015): Xinjiang, Northwest China	Land- and water-use development were mainly influenced by population development and water resource availability, followed by the development of agricultural yields, the technological progress regarding water-use efficiency and the overall economic development in the region.	NA
Meyfroidt (2013b): Northern mountains of Vietnam	Forest changes were influenced by anthropogenic factors (including activities from outsiders), natural regeneration of forest, and natural hazards.	Mostly have no early detection and recognition of environmental change because of very rapid changes or slow trend of degradation.
Yu et al. (2013): Heilongjiang, Northeast China	Land transfer and crop choice decisions were mainly influenced by education level, the initially allocated land rights, infrastructure, crop prices, market, policy, cropping technology, and agricultural disasters. While climate change has no significant influence.**	NA
Yu et al. (2014): Heilongjiang, Northeast China	NA	A small portion (~5%) of interviewees did not perceive any climate change, even though an obvious temperature increase and precipitation decrease were observed. Moreover, about 25% perceived a decreased temperature and about 30% perceived an increased precipitation, showing they perceived changes in the wrong direction. Furthermore, no obvious changes in agricultural disasters were observed and perceived.*
Liu and Liu (2016): Shanghai, East China	Rural livelihood transitions were mainly influenced by age, education, wage, crop prices, policies, subsidies, machinery, activities organized by local agricultural cooperatives, and land rent.**	NA

cannot be explained from the observed changes in environmental conditions only. Moreover, Yu et al. (2013) noted that the perception of climate change is not directly translated into decision-making: the attitude scores indicate that precipitation and temperature are hardly important in the farmer's decisions. By contrast, agricultural disasters, a factor that was not perceived as changing, played a significant role in determining local farmers' crop choices. This leads to the interesting observation that an incorrectly perceived environmental change may still affect decisions.

3.3. Illustrations of environmental cognitions as mediators

The Northeast China cognition-based cases are further compared to the main conclusions from 23 publications that explored the causes of agricultural land change in Northeast China focusing on the underlying driving forces (Framework B in Figure 1) and from 18 publications focusing on actors' characteristics (Framework C in Figure 1), in order to illustrate how environmental cognitions mediate the causal explanation of agricultural land change. The more extensive description of the Northeast China cases and a list of these selected publications and the criteria of inclusion are presented in the Electronic Supplementary Material.

Figure 4 clearly shows that environmental change has led to variations of individual decision-making through the mediation of environmental cognitions. For example, climate variables, especially changes in temperature and precipitation, are the most important factors determining the agricultural potential in Northeast China given the recent global warming trend. Temperature and precipitation have been identified 11 and 8 times as a cause for agricultural land change, respectively (Figure 4, green box). However, these two factors have not been validated from the perspective of environmental cognition (brown box in Figure 4, and text above). Moreover, while socioeconomic factors such as off-farm income, agricultural input, and policies implemented during the recent institutional reforms are also believed to impact agricultural land changes (Figure 4, green box), only policy has been acknowledged by environmental cognition (Figure 4, brown box). By contrast, other factors, including market, infrastructure, crop production, technology and agricultural disasters that are merely identified in the green box (Figure 4, green box), have been perceived as determinants for land change (Figure 4, brown box). In addition, Figure 4 shows discrepant causal explanations between actor characteristics and environmental cognitions: while age, labour and off-farm income are frequently identified as causes (Figure 4, dark purple box), farmer seldom believe their land use decisions are determined by those factors. Instead, they tend to believe that education has substantially affected their decision-making: for example, some cash crop cultivation requires specific vocational education, which is easily excluded in the standardized questionnaires which usually acquire education level as the proxy. The illustration not only supports the PAD as an operationalization of environmental cognitions, but also helps to understand environmental cognitions as the mediators in the land change process.

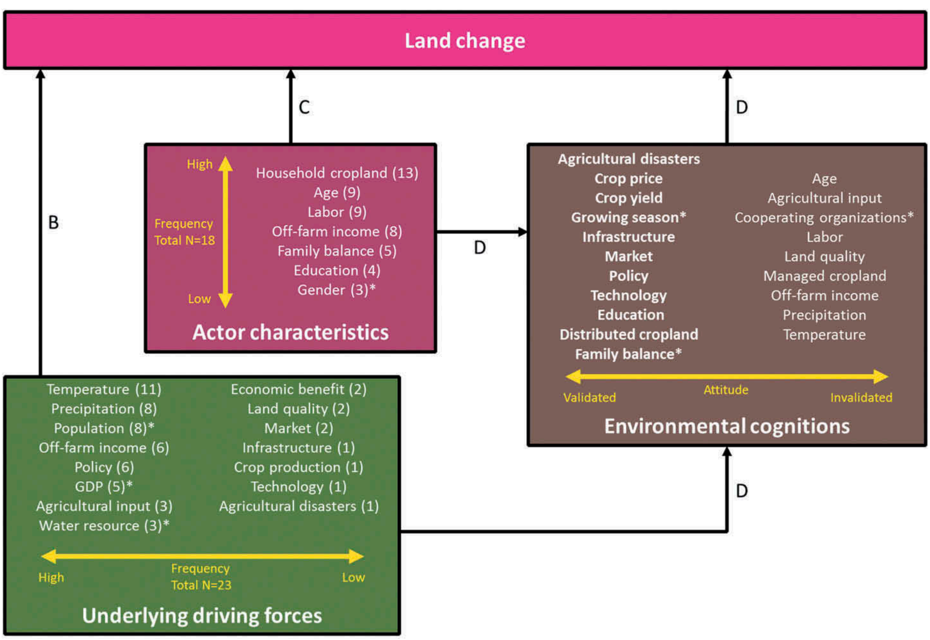

Figure 4. Causal explanations of agricultural land change for the cross-framework integration.

4. Discussion and conclusions

4.1. Improved conceptualization of land change processes

Land system science and the conceptualization of land change causal explanations are co-developing. Firstly, the framework of proximate causes and underlying driving forces was largely a result of widely available 'pixel-based' research, while the inclusion of actors stimulated the development of 'agent-based' studies (van Vliet et al., 2016). Secondly, multi-faceted land use decisions made by individual actors lead to the multi-characterization of land systems. Therefore, the *explanandums* in the causal analysis are broadened from land cover to land use, land management, and provisioning of ecosystem services as well, which need a specification of problems before the generation of hypotheses to explain changes (Efroymson et al., 2016).

A more detailed conceptualization of causal explanations is characterized by the prolonged causal chain, through which the extra causal mechanisms are added. As shown in Figure 1, the role of individual actors is firstly elicited in Framework C. At this stage, the attributes of actors (e.g. personal characteristics) are normally considered in addition to the socioeconomic and biophysical conditions (Smajgl, Brown, Valbuena, & Huigen, 2011). Many actor-based studies project potential future decisions in a hypothetical context, rather than measuring and explaining the actual decisions made in real-world settings (Kühberger, Schulte-Mecklenbeck, & Perner, 2002; Schlüter et al., 2017). The ways for representing behaviour include optimization approaches, such as the rational decision model, experimental approaches, such as role-playing games and choice experiments (Paulrud & Laitila, 2010), and heuristic approaches, such as theory of reasoned action and belief-desire-intention model (Nilsson, von Borgstede, & Biel, 2004). Optimization approaches explain what decisions people 'ought' to make, based on personal characteristics and other conditions. Experimental approaches analyse people's behaviours in an artificial context, thereby neglecting the cognitive aspects related to observing the real world. Heuristic studies, on the other hand, attempt to explain the processes of decision-making by assuming a stable set of preferences, beliefs, and decision rules interacting with actors' personal characteristics. Regardless of the approach, cognitions are barely analysed in a comprehensive manner in land system science (Meyfroidt, 2013a), e.g. many studies overlooked the formation and modifications of beliefs, attitudes, preferences or utility function, and/or heuristics in a changing environment. Cognitions are, therefore, formed in a black box, playing a similar role as personal characteristics, rather than the adapters connecting deferent components in the decision-making processes.

Eliciting environmental cognitions, such as in Framework D of Figure 1, is able to decompose the black boxes of decision-making to a certain extent. They represent the adaptive processes linking the conditions and behaviours, which are substantially differed from the stabilized cognitions such as belief, preference, and willingness, and are able to form an independent set of causes – in addition to personal characteristics – to function as the mediating variables. As a result, inferences on a more convincing causal explanation would be possible through such discretization. However, a more detailed framework inevitably requires more detailed (interview) data, which is often time and labour-intensive to obtain, indicating that there is a trade-off between details and resource availability need to be properly addressed for case studies. We believe land system science can be further enriched by 'process-oriented' studies, which are characterized by advanced operationalization of the mediating mechanism in land change processes.

4.2. The PAD measurement and beyond

Schlüter et al. (2017) reviewed the behavioural theories in models of social-ecological systems. As one of these alternatives, the proposed PAD measurement is clearly contextualized in the generalized causal chain connecting elements between underlying driving forces and land changes, which might help to compare and synthesize causal explanations yielded from different analytical frameworks. For example, the illustration of PAD in Northeast China indicates that the impact of underlying driving forces on agricultural land change has been mediated by environmental cognitions: land change based on direct representations of underlying conditions would assume a larger impact from conditions (e.g. climate change in the case study region) by ignoring the decision-making process. While environmental cognitions are object-specific, which raises the awareness that the same underlying conditions are substantially mediated by the same actor, bringing about dissimilar causal explanations to different aspects of decisions. Environmental cognitions are also actor-specific, which explains why actors who share similar characteristics and live in similar environments can make different decisions. This means that although policymakers can manage a land system based on their understanding of its underlying conditions, it would be as important to design human-centered policies at a local scale by understanding the cognitive processes underpinning stakeholders' decisions.

Moreover, the proposed PAD measurements might help to evoke ideas and stimulate debate of developing new approaches for the operationalization of environmental cognitions as mediating variables in the causal analysis of land change. It also provides a structure for further elaboration of the cognitive processes for understanding human-environment interactions. First, perception, attitude, and decision, as applied to agricultural land change, can also be applied to the broader land system science. For example, in urbanization studies, perception could focus on changes in house prices and job opportunities rather than on the length of growing season and precipitation. It is important, however, to note the differences in perception, attitudes, and decisions when applying them in other studies. Second, the role of location and environment cannot be assessed by a single case study. Therefore, similar studies are needed to assess the environmental cognitions of people living in urban and rural areas or people from regions with different cultural backgrounds. Capturing the heterogeneity across human geographies would provide insight into human-environment interactions by allowing cross-site comparisons and meta-studies (van Vliet et al., 2016). Finally, the insights from PAD measurements could facilitate the design of agent-based models (Magliocca et al., 2015). While several such models have been presented for simulating land change, designing, comparing and parameterizing the decision-making algorithms in these models remains a challenge (Smajgl et al., 2011).

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